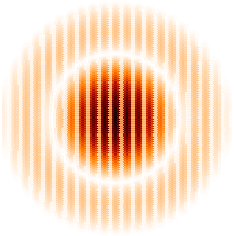


Imaging with Aperture Masking

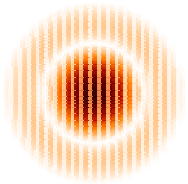
John D. Monnier

Harvard-Smithsonian Center for Astrophysics

Collaborators

Peter Tuthill (Sydney)

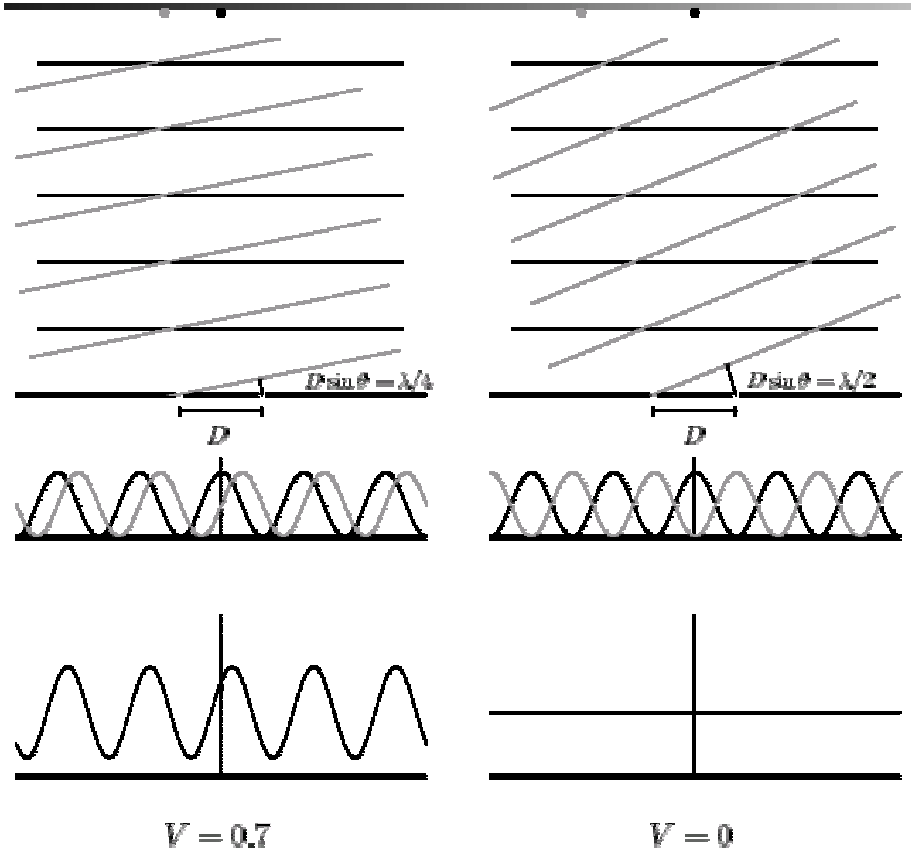
Bill Danchi (NASA-GSFC)



Outline

- Brief review of closure phases and principles of aperture synthesis imaging
- The visibilities and closure phases
  - How do we get them with aperture masking
  - How good are they?
- Imaging with Keck aperture masking
  - Stuffing the data into a VLBI package
  - Deconvolution and aperture synthesis
  - Examples of Maximum Entropy Method
  - Some Keck results illustrating data quality
- Problems with the status quo

Stellar Interferometry



Basics

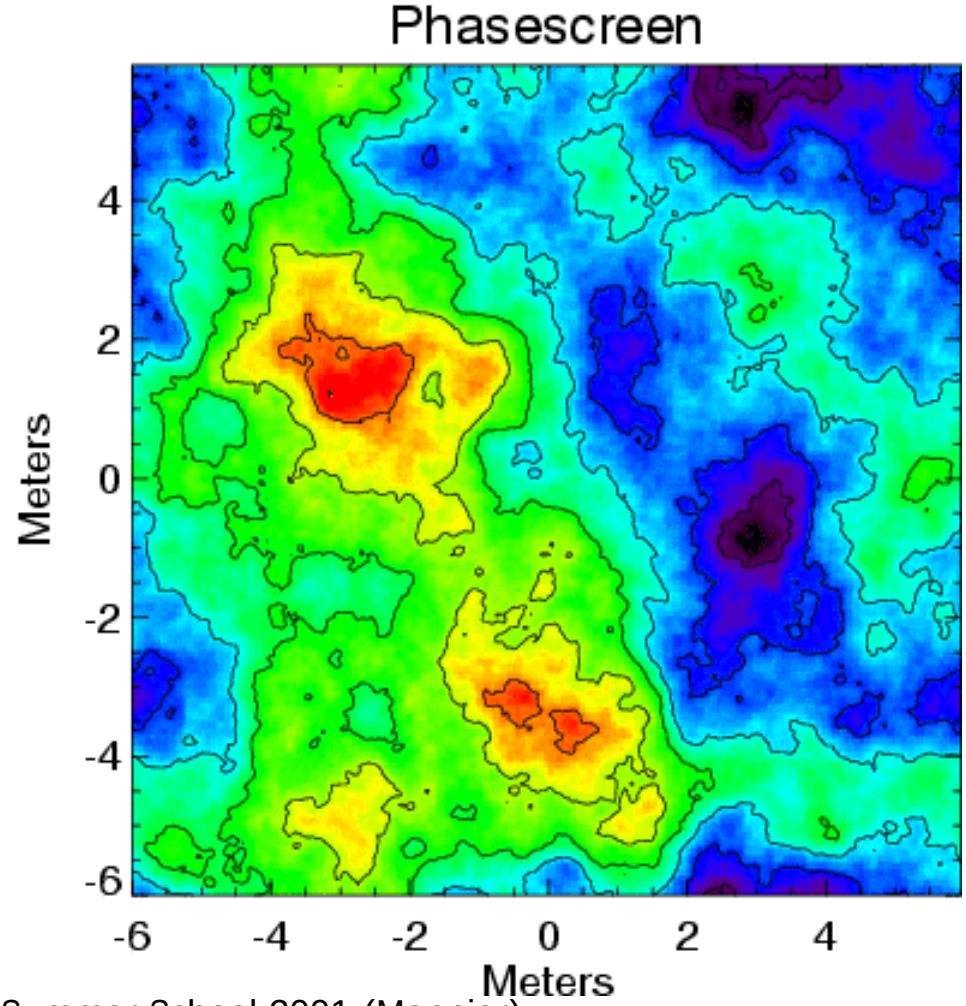
- The amplitude of fringe corresponds to Fourier amplitude of a single Fourier component of brightness distribution
- The phase corresponds to the Fourier phase
- Collecting enough of these amplitudes and phases, at different slit separations and position angles, allows the image to be reconstructed

Lipman Thesis 1998

Fringe Visibility: $V_M \equiv \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$

Michelson Summer School 2001 (Monnier)

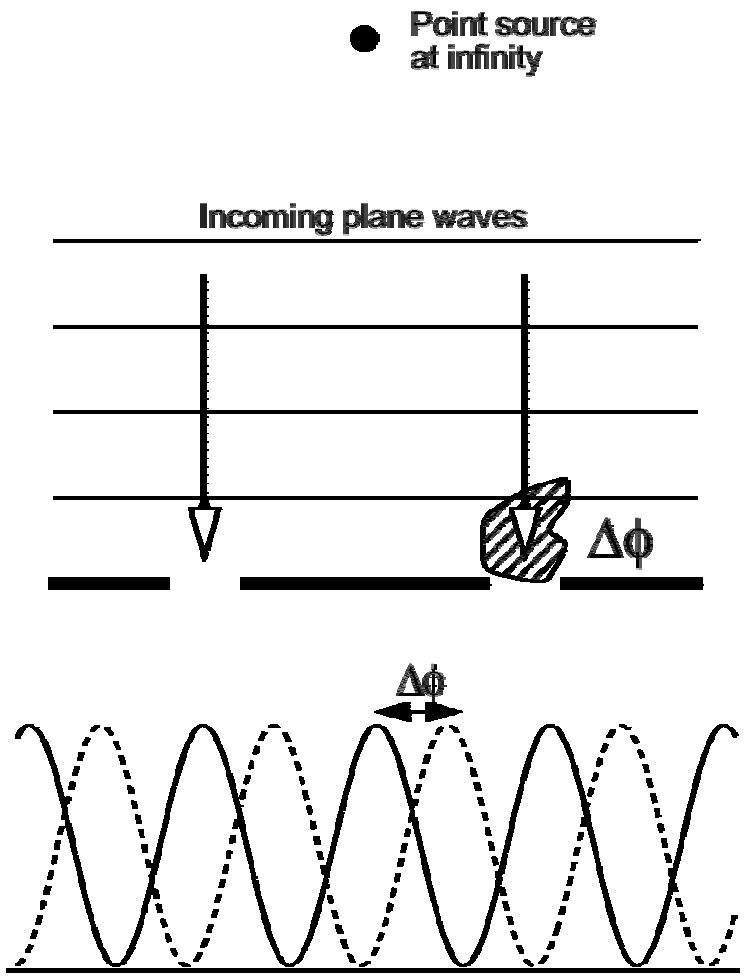
The Atmosphere...



A Keck-sized patch of atmosphere during typical good seeing

Each contour is one radian of phase delay of 2-micron light

Atmosphere Corrupts the Phase



Telescope-based Errors

$$\begin{aligned}\tilde{E}_i^{\text{measured}} &= \tilde{G}_i \tilde{E}_i^{\text{true}} \\ &= |G_i| e^{i\Phi_i^G} \tilde{E}_i^{\text{true}}.\end{aligned}$$

Telescope Gain
(e.g., coupling efficiency into single-mode fiber)

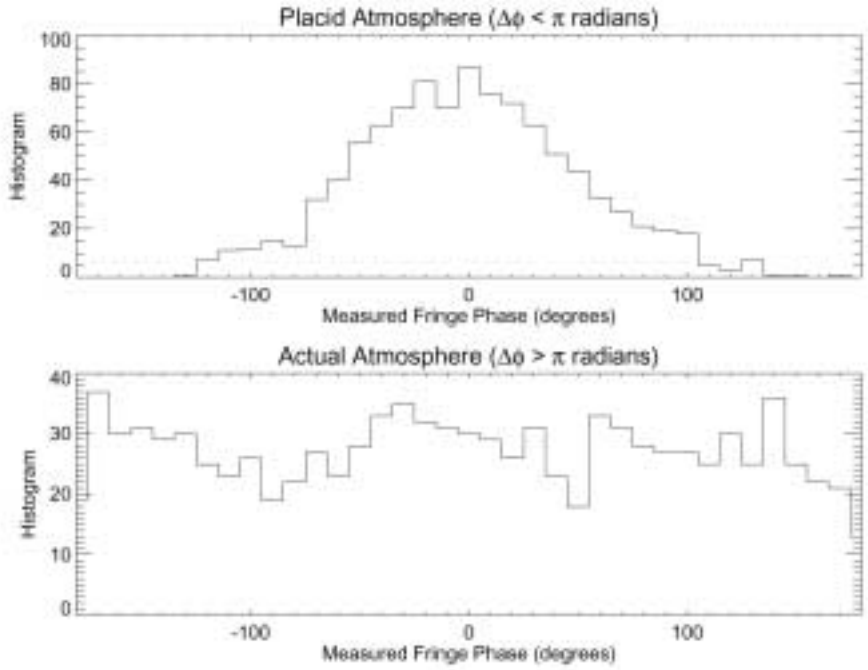
Telescope Phase Shift
(e.g., atmospheric piston, bad baseline, thermal drifts)

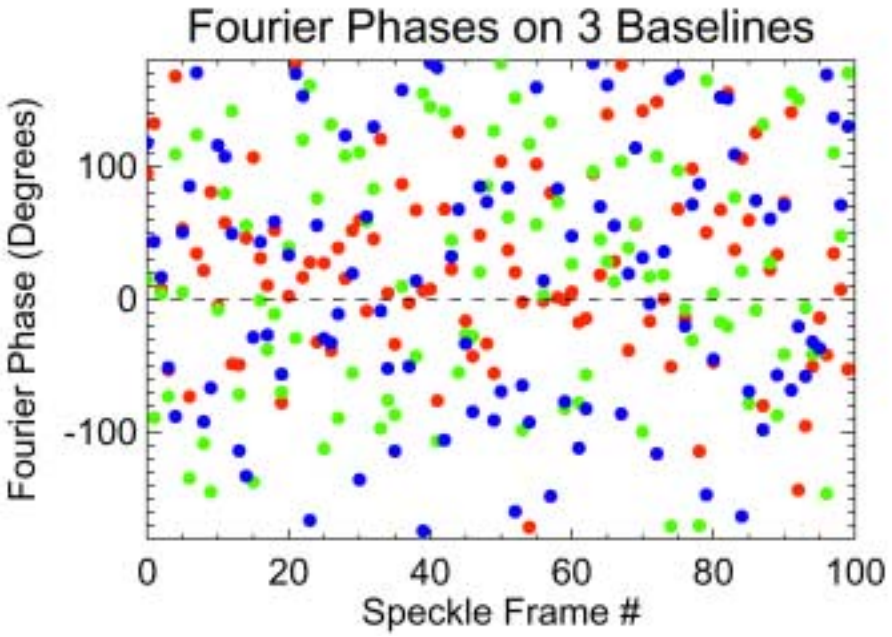
$$\text{Since} \quad \tilde{\mathcal{V}}_{ij} \propto \tilde{E}_i \cdot \tilde{E}_j^*,$$

$$\begin{aligned}\tilde{\mathcal{V}}_{ij}^{\text{measured}} &= \tilde{G}_i \tilde{G}_j^* \tilde{\mathcal{V}}_{ij}^{\text{true}} \\ &= |G_i||G_j| e^{i(\Phi_i^G - \Phi_j^G)} \tilde{\mathcal{V}}_{ij}^{\text{true}}\end{aligned}$$

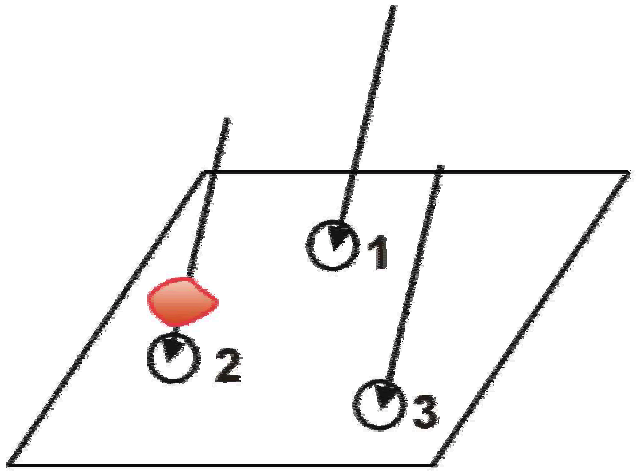
Phase shift of detected Fringe

Big trouble…


Placid Atmosphere (Δφ < π radians)
Histogram
Measured Fringe Phase (degrees)
Actual Atmosphere (Δφ > π radians)
Histogram
Measured Fringe Phase (degrees)


Fourier Phases on 3 Baselines
Fourier Phase (Degrees)
Speckle Frame #

The "Closure Phase" Is Not Corrupted



Observed = Intrinsic + Atmosphere

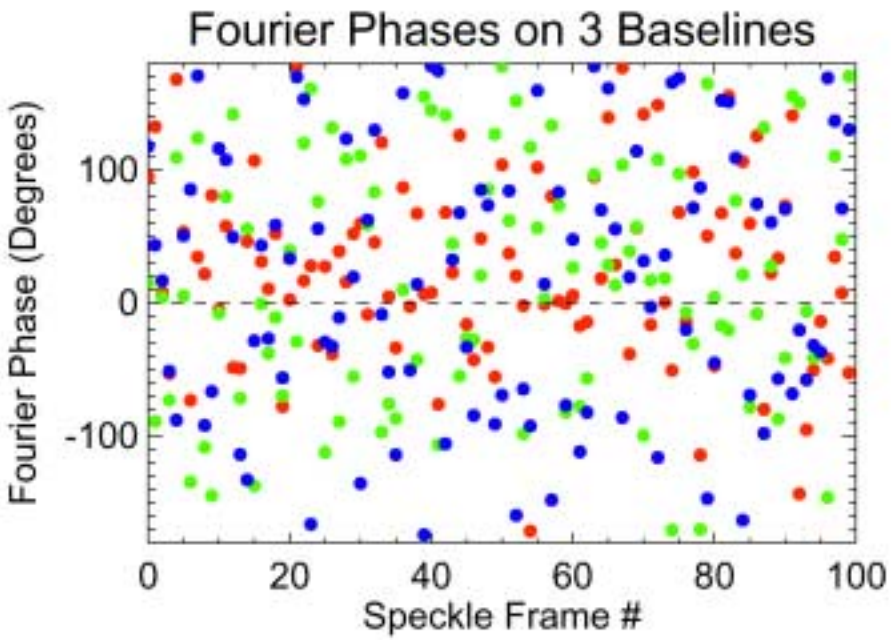
$\Phi(1\text{-}2) = \Phi_o(1\text{-}2) + [\phi(2)\text{-}\phi(1)]$
$\Phi(2\text{-}3) = \Phi_o(2\text{-}3) + [\phi(3)\text{-}\phi(2)]$
$\Phi(3\text{-}1) = \Phi_o(3\text{-}1) + [\phi(1)\text{-}\phi(3)]$

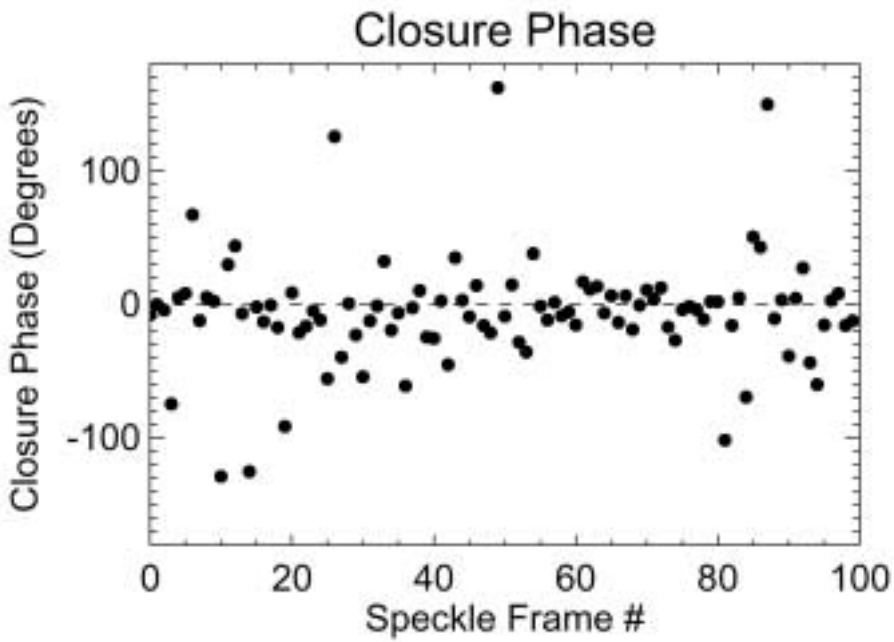
Closure Phase (1-2-3) $= \Phi_o(1\text{-}2) + \Phi_o(2\text{-}3) + \Phi_o(3\text{-}1)$

Related to the Bispectrum B_{ijk}, used in Speckle Interferometry

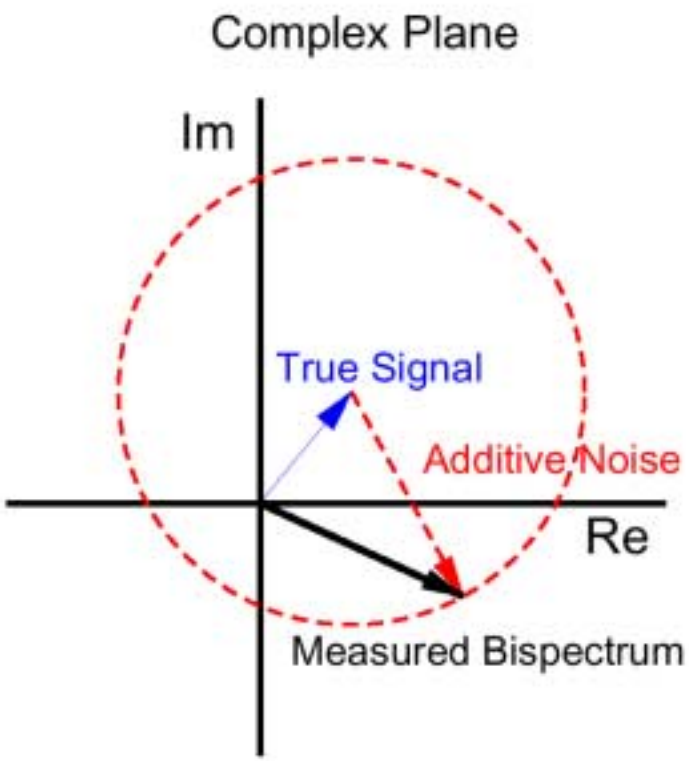
$$\begin{aligned}
\tilde{B}_{ijk} &= \tilde{\mathcal{V}}_{ij}^{\text{measured}}\,\tilde{\mathcal{V}}_{jk}^{\text{measured}}\,\tilde{\mathcal{V}}_{ki}^{\text{measured}} \\
&= |G_i||G_j|\,e^{i(\Phi_i^G-\Phi_j^G)}\,\tilde{\mathcal{V}}_{ij}^{\text{true}}\cdot|G_j||G_k|\,e^{i(\Phi_j^G-\Phi_k^G)}\,\tilde{\mathcal{V}}_{jk}^{\text{true}}\cdot|G_k||G_i|\,e^{i(\Phi_k^G-\Phi_i^G)}\,\tilde{\mathcal{V}}_{ki}^{\text{true}} \\
&= |G_i|^2\,|G_j|^2\,|G_k|^2\,\tilde{\mathcal{V}}_{ij}^{\text{true}}\cdot\tilde{\mathcal{V}}_{jk}^{\text{true}}\cdot\tilde{\mathcal{V}}_{ki}^{\text{true}}.
\end{aligned}$$

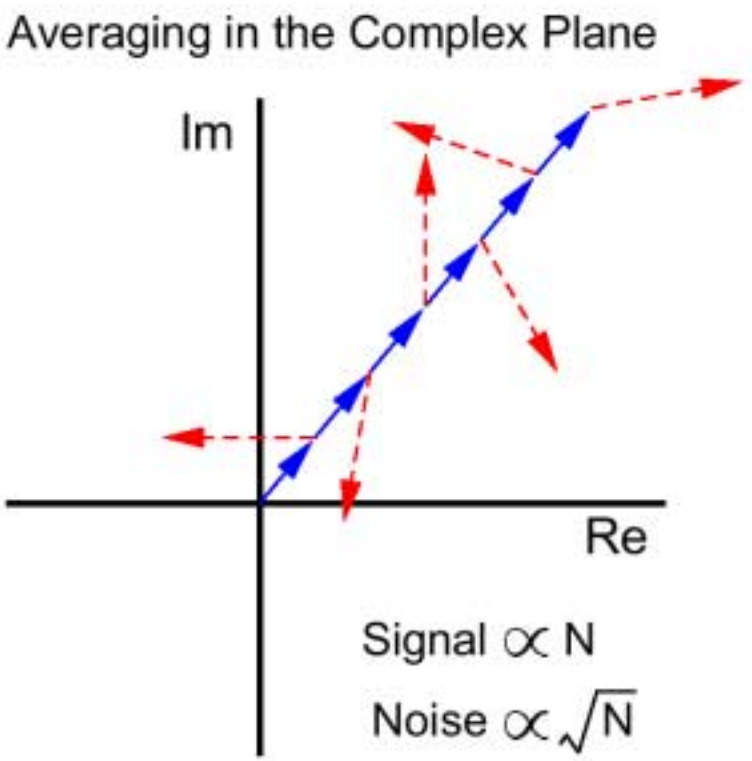
Closure Phase is a Good Observable





Closure Phase Averaging





How Much Phase Information?

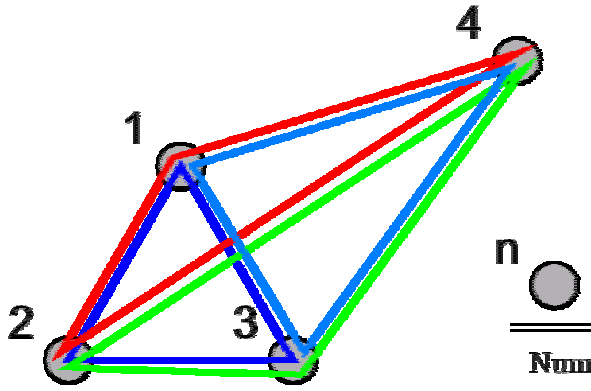
Closure Phases are not all independent from each other.

Number of Closure Phases

$$\binom{N}{3} = \frac{(N)(N-1)(N-2)}{(3)(2)},$$

Number of Fourier Phases

$$\binom{N}{2} = \frac{(N)(N-1)}{2}$$



Number of Independent Closure Phases

$$\binom{N-1}{2} = \frac{(N-1)(N-2)}{2}$$

Number of Telescopes	Number of Fourier Phases	Number of Closing Triangles	Number of Independent Closure Phases	Percentage of Phase Information
3	3	1	1	33%
7	21	35	15	71%
21	210	1330	190	90%
27	351	2925	325	93%
50	1225	19600	1176	96%

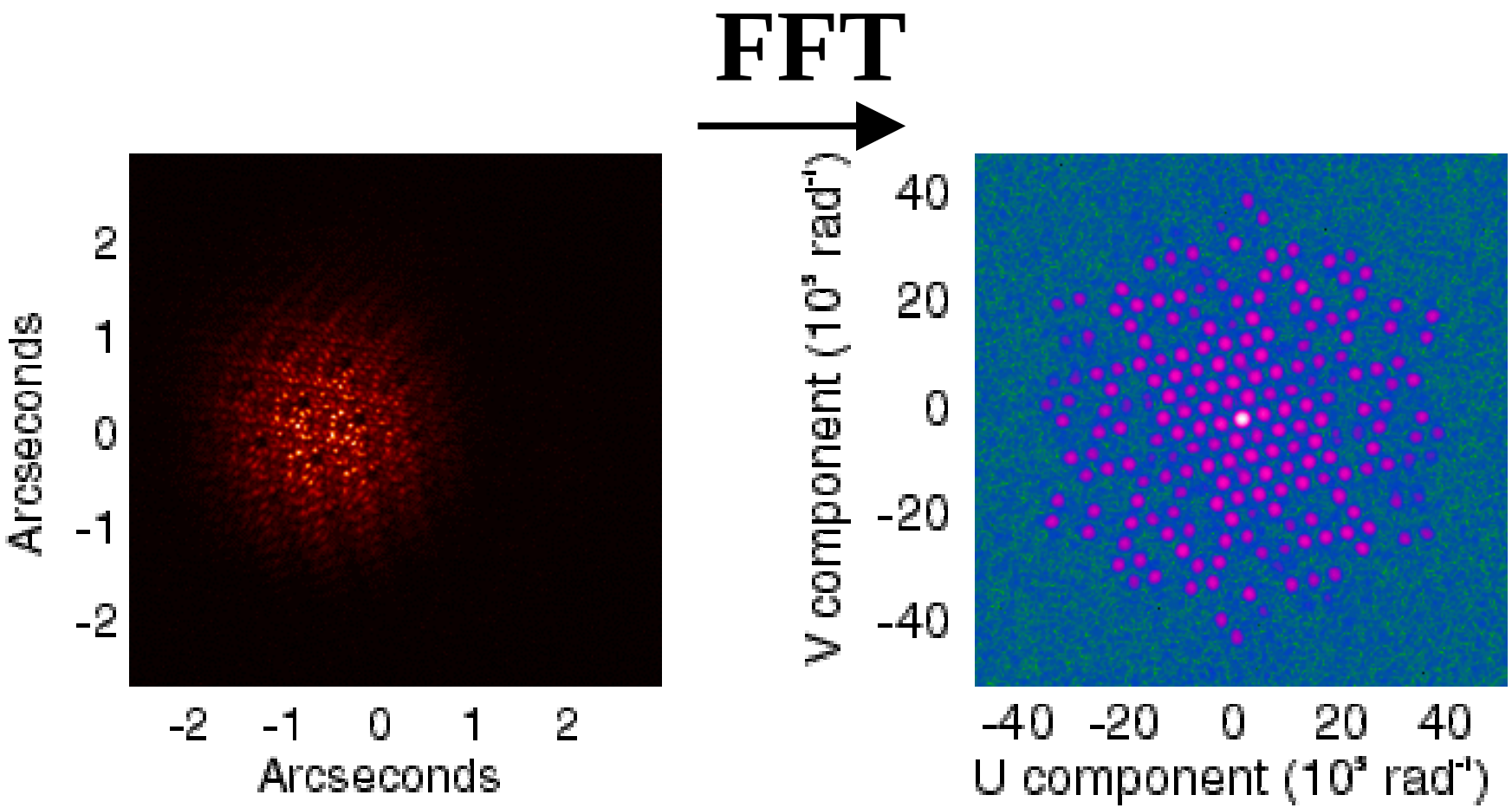
Closure Amplitudes too

$$
\begin{aligned}
A_{ijkl} &= \frac{|\tilde{\mathcal{V}}_{ij}^{\text{measured}}||\tilde{\mathcal{V}}_{kl}^{\text{measured}}|}{|\tilde{\mathcal{V}}_{ik}^{\text{measured}}||\tilde{\mathcal{V}}_{jl}^{\text{measured}}|} \\
&= \frac{|\tilde{G}_i||\tilde{G}_j||\tilde{\mathcal{V}}_{ij}^{\text{true}}||\tilde{G}_k||\tilde{G}_l||\tilde{\mathcal{V}}_{kl}^{\text{true}}|}{|\tilde{G}_i||\tilde{G}_k||\tilde{\mathcal{V}}_{ik}^{\text{true}}||\tilde{G}_j||\tilde{G}_l||\tilde{\mathcal{V}}_{jl}^{\text{true}}|} \\
&= \frac{|\tilde{\mathcal{V}}_{ij}^{\text{true}}||\tilde{\mathcal{V}}_{kl}^{\text{true}}|}{|\tilde{\mathcal{V}}_{ik}^{\text{true}}||\tilde{\mathcal{V}}_{jl}^{\text{true}}|}.
\end{aligned}
$$

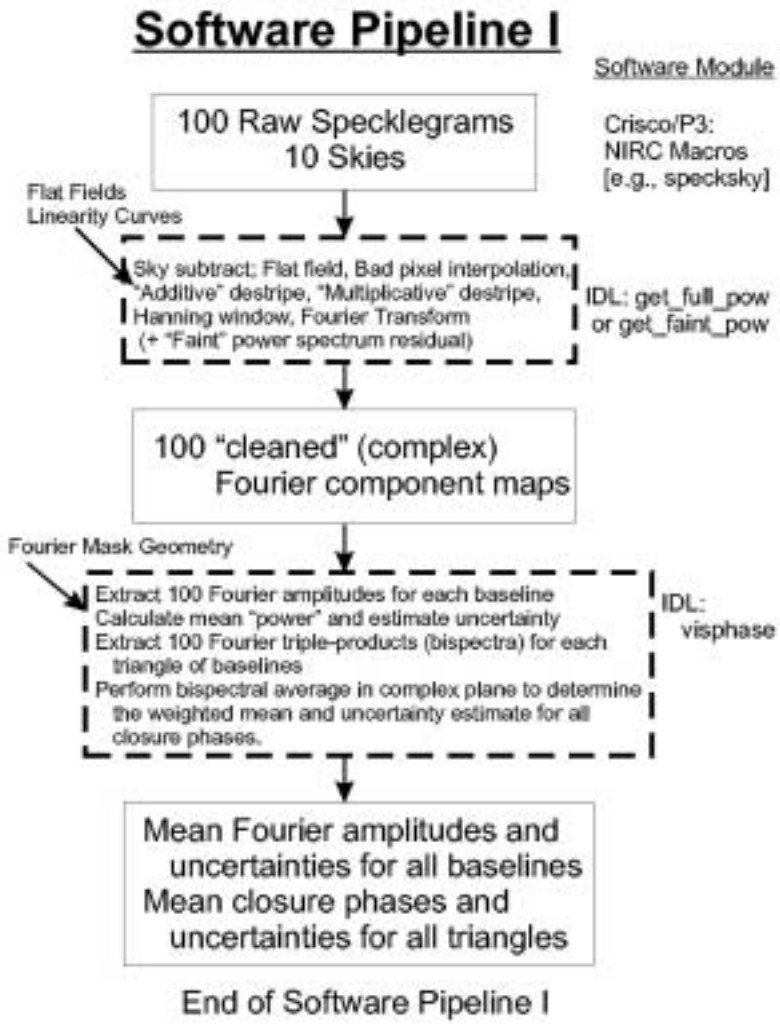
Closure amplitudes have not been used effectively in optical interferometry because fringe amplitude fluctuations are mostly caused by variable atmospheric coherence (and because there are few 4-telescope arrays).

However, closure amplitudes should be useful for interferometers using spatial filters such as single-mode fibers.

Speckles and Power Spectra

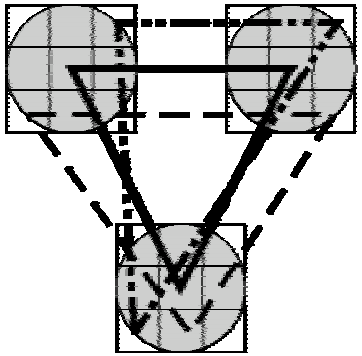


Software Pipeline I

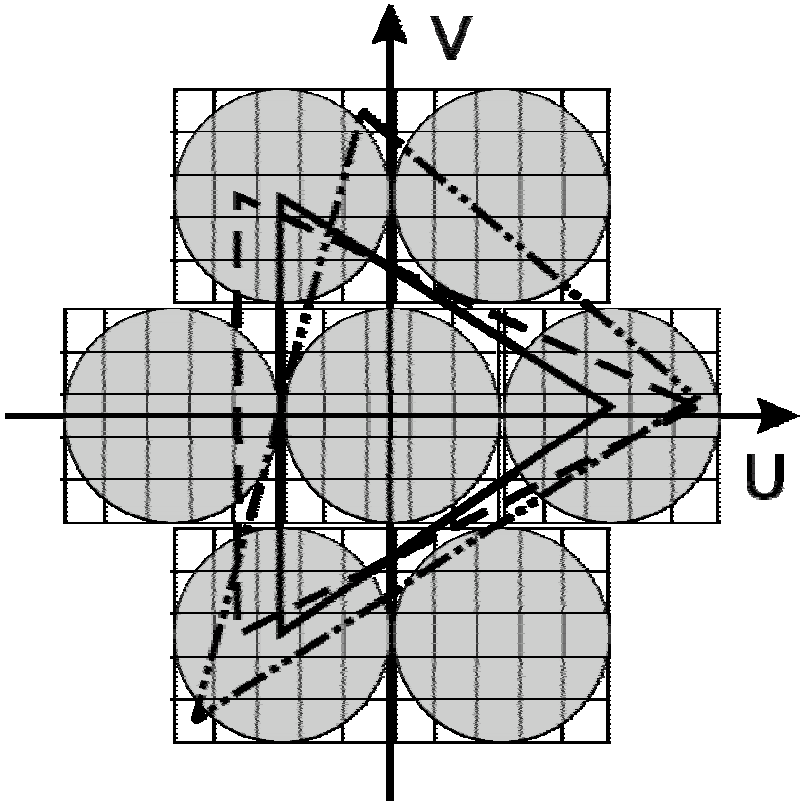


Averaging the Visibility^2

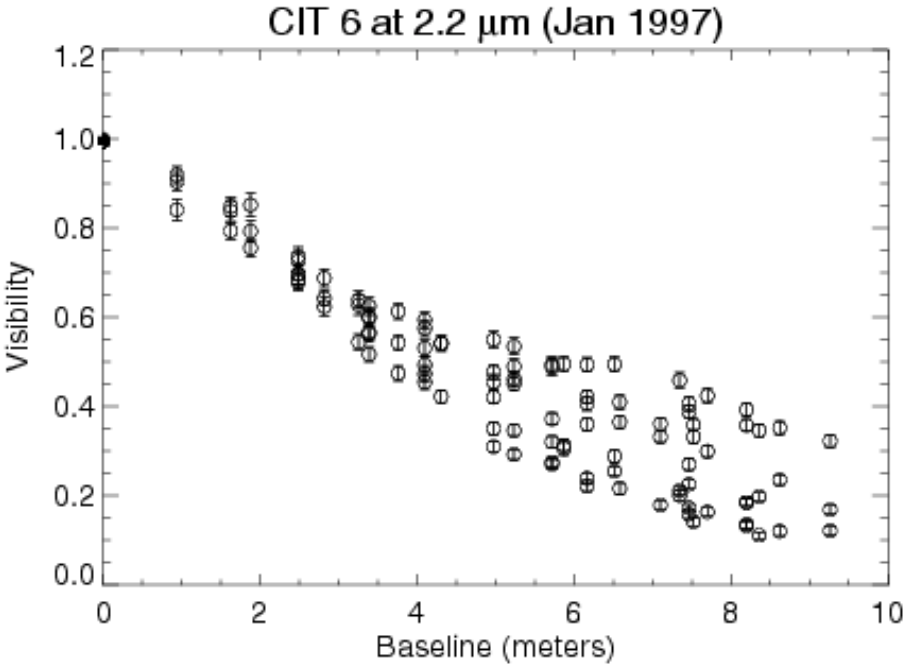
Simple Mask

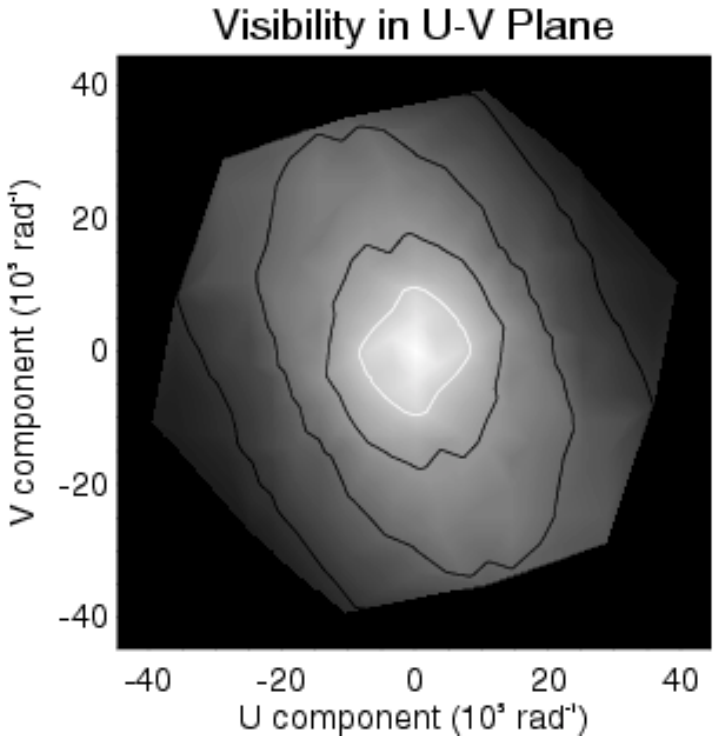


Fourier Plane



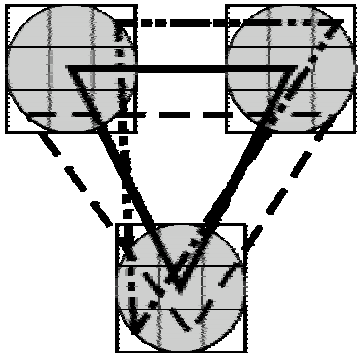
Analyzing The Amplitudes...



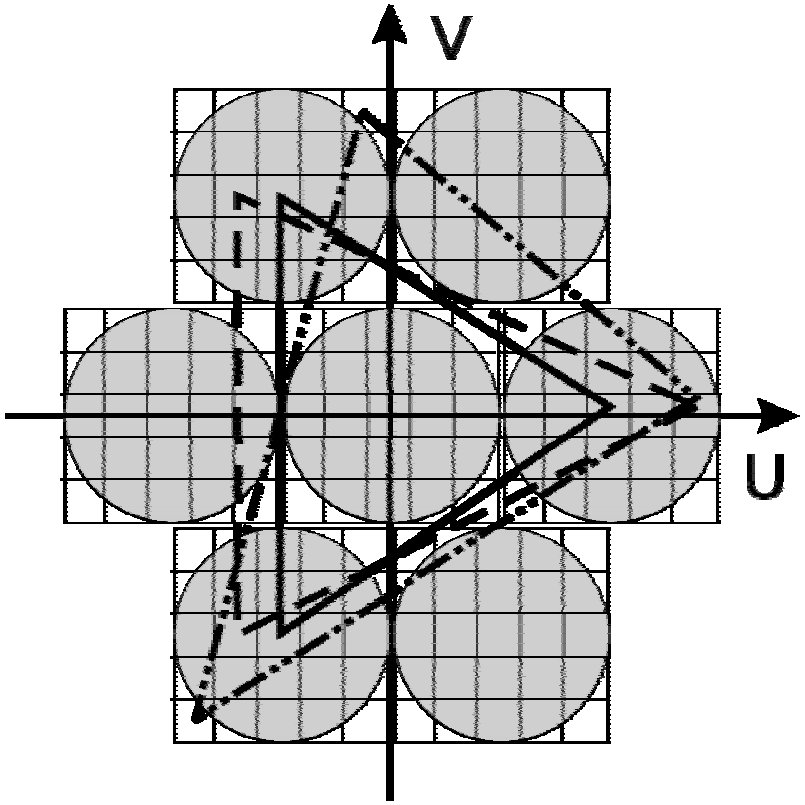


Closure Phase Averaging

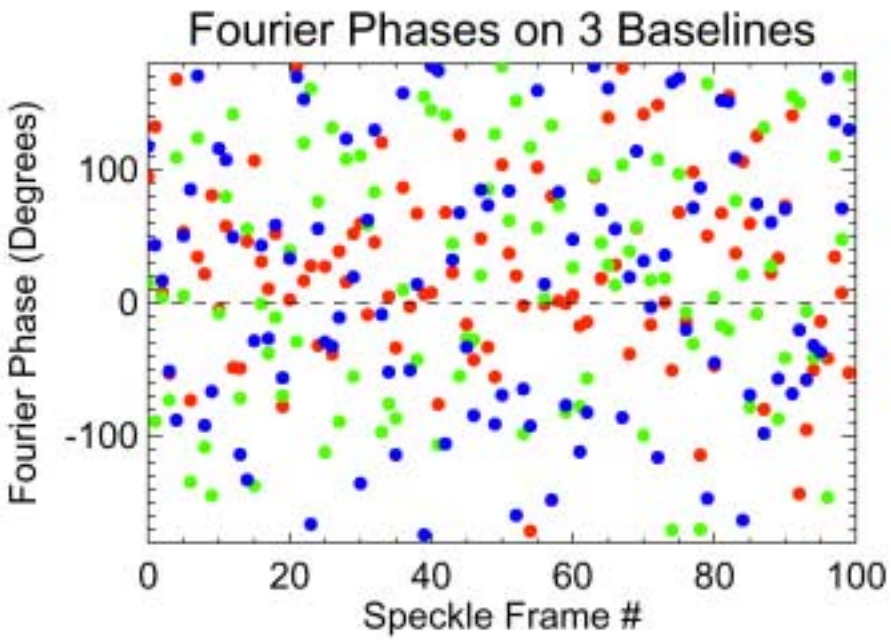
Simple Mask

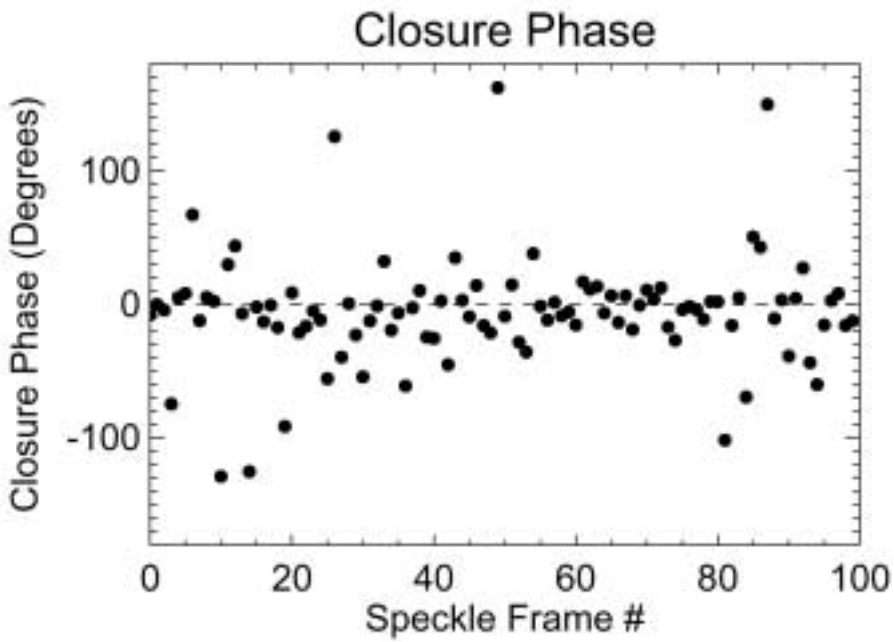


Fourier Plane



Closure Phase is a Good Observable





Closure Phase is a Good Observable